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The Meteorological Conditions of Precipitation Deficits in the Cultivation of Winter Wheat in Central and Eastern Poland

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ABSTRACT

The problem of precipitation deficits constitutes an issue that is significant on a global, regional, and local scale, particularly in the aspect of climate warming. The purpose of this research was to determine the amount, frequency and trends of precipitation deficits in the cultivation of winter wheat in central and eastern Poland, over a period of fifty years (1971–2020). This study used the values of average monthly air temperatures, as well as monthly total precipitation, decadal precipitation needs of winter wheat within central and eastern Poland. Based on the performed research, both spatial and temporal differences were observed in the scope of the amount and frequency of precipitation deficits in the cultivation of winter wheat. The lowest risk of precipitation deficits was found in May (from 15% to 32%), which is a critical month in the cultivation of this plant in Poland, while the highest risk of precipitation deficits was observed in June (from 22% to 56%), which is an unfavourable phenomenon, because winter wheat is in the so-called grain filling phase since mid-June. It was also found that there is a statistically significant upward trend of the winter wheat's precipitation needs in April, June, and July. An increase in the inflow of warm and dry air masses from the southern sectors was one of the factors impacting the amount and frequency of precipitation deficits in the cultivation of wheat. The problem of climate warming that has been increasing in recent years, and – as a consequence – an increase in precipitation deficit during the growing season of plants, demonstrate the need for further research in this scope.

Keywords: air temperature, total precipitation, atmospheric circulation, precipitation deficits, winter wheat, Lublin region.

INTRODUCTION

Some of the greatest threats to our modern world include climate change, an increase in air temperature, as well as more and more frequent extreme weather phenomena, the intensification of which has been observed especially in the last 20 years of the 21st century (Intergovernmental Panel on Climate Change, 2007). The above–mentioned changes, particularly a significant air temperature increase and occurrence of periods without precipitation, especially in the phase of the plants' greatest demand for water, constitute the factors that intensify the water deficit and pose a considerable threat to crops (Jadczyszyn and Bartosiewicz, 2020).

The most vulnerable to the effects of climate change is particularly plant production. Plants are characterised by two sources of natural water supply. The first and direct water source for plants in the field conditions consists of water resources in the soil, while the second one is precipitation, which is an indirect source (Durau and Żarski, 2013).

In the case of Poland, over 50% of agriculturally used areas are soils characterised by low water retention and deep groundwater level. As a result of these conditions, precipitation constitutes the main source of water supply for plants (Kaczmarczyk and Nowak, 2006; Durau and Żarski, 2013). In crop production, not only the annual total precipitation is significant, but also the frequency, amount, as well as duration of precipitation during the growing season, particularly within critical periods, i.e. in the periods of the plants' highest water demand (Rzekanowski, 2009).

The changeability of thermal conditions and precipitation in Poland primarily results from the air masses that shape different types of weather. During the year, Central Europe is dominated by the western zonal circulation, associated with the influx of more humid air masses from the Atlantic Ocean (Niedźwiedź and Ustrnul, 2021). In this part of Europe, the meridional circulation plays a smaller role and usually forms during the occurrence of high-pressure zones over the continent (Bartoszek and Kaszewski, 2022). The appearance of high-pressure zones over Eastern Europe from spring to the beginning of autumn is conducive to the advection of warm and dry continental air masses over Poland, which is usually accompanied by long-lasting warm spells, as well as periods without precipitation (Araźny et al. 2021).

Wheat (*Triticum L.*) is one of the most important crops in the global production of plants. As a raw material for bread and fodder, wheat grain is characterised by strategic significance in the scope of ensuring food security at the global level. The demand for wheat increases along with the increase in the global population (Igrejas and Branlard, 2020). Common wheat is the cereal with the largest cultivation acreage in Poland (over 2 million ha) (Statistics Poland, 2021).

The average distribution of precipitation in Poland is rather not conducive to achieving high yields of winter wheat (Jasińska and Kotecki, 2003).

While taking into account the temporal and spatial variability of precipitation in the region of Central Europe, the research concerning precipitation deficits in the cultivation of such a strategic cereal as winter wheat is very important, as well as characterised by high practical significance, particularly in the aspect of adaptation of crop production to climate change. The purpose of this study was to determine the amount, frequency, and trends of precipitation deficits in the cultivation of winter wheat in central and eastern Poland, in the period of fifty years (1971–2020). Furthermore, it assesses the impact of atmospheric circulation on precipitation deficits, in relation to the inflow frequency of the air masses that are different in terms of humidity and thermal properties.

MATERIALS AND METHODS

Research area

This research was conducted in the area of central and eastern Poland, where the Lublin Province is located. The Lublin Province is situated within two basin areas of the following rivers: upper Vistula, Bug, and Narew. This province ranks third in the country in terms of area, which amounts to 2512.3 thousand ha, while the area of agricultural land amounts to 1353.9 thousand ha. The Lublin region is one of the least industrialised regions, and at the same time one of the most important agricultural regions in our country. Beneficial soil and climatic conditions result in the fact that this area is characterised by favourable conditions for agricultural activity. The sowing structure in the Lublin Province is dominated by cereals, which constitute 74.4% of the total sowing amount. Winter wheat is cultivated here in the acreage of 299.6 thousand ha (in Poland: 2 218.0 thousand ha), with the optimal sowing period in the second half of September, while its harvest is usually carried out in July of the following year (Statistical Office in Lublin, 2019).

The high variability of individual weather elements, including precipitation and air temperature, is a distinguishing feature of the climatic conditions occurring in the Lublin region (Bartoszek and Kaszewski, 2022). Higher average annual atmospheric air temperatures (8.5 °C) occur in the Lublin region's western part – in the Vistula river valley, while lower ones occur in the north-eastern part of the province: 7.8 °C and in the south-eastern part: 8.1 °C (the basin area of the Bug and Narew rivers). The highest increases in average monthly air temperature (starting from the 1970s) in the research area were recorded in April, June, July, and August, i.e. during the months of the warm half-year.

Precipitation within the Lublin region is characterised by a high spatial and temporal variation. In spatial terms, the highest total annual precipitation amounting to 650–750 mm is recorded in the southern part of the Province – in the Roztocze macroregion, which is characterised by the highest location above sea level, i.e. >300 m above sea level (the basin area of upper Vistula) (Figure 1). In the Lublin region's northern part, i.e. in Polesie Lubelskie (250 m above sea level), the total annual precipitation does not exceed 520–550 mm (the basin area of Bug and Narew). The lowest precipitation occurs during winter. July is the wettest month with an average total precipitation amounting from 71 to 86 mm, while in January it does not exceed 32 mm. In individual seasons of the year, precipitation is characterised by high variability in terms of intensity as well as duration. Winter and autumn precipitation is usually low and long–lasting, while summer precipitation is shorter, but more intense.

Precipitation and thermal conditions depend on the atmospheric circulation to a considerable extent. On a year-to-year basis, slightly dominant here are the high-pressure systems, which are responsible for the weather that is not conducive to the occurrence of precipitation (Kaszewski, 2008).

Research material

The research used monthly values of average air temperature, as well as total precipitation values from the period of 1971–2020, and decadal precipitation needs of the winter wheat cultivated on medium-cohesive soils (which dominate in this part of Poland). Meteorological data originated from 11 measurement stations (Siedlce, Cicibór, Terespol, Włodawa, Bezek, Puławy, Czesławice, Radawiec, Felin, Zamość, Sandomierz) belonging to the Institute of Meteorology and Water Management – National Research Institute,

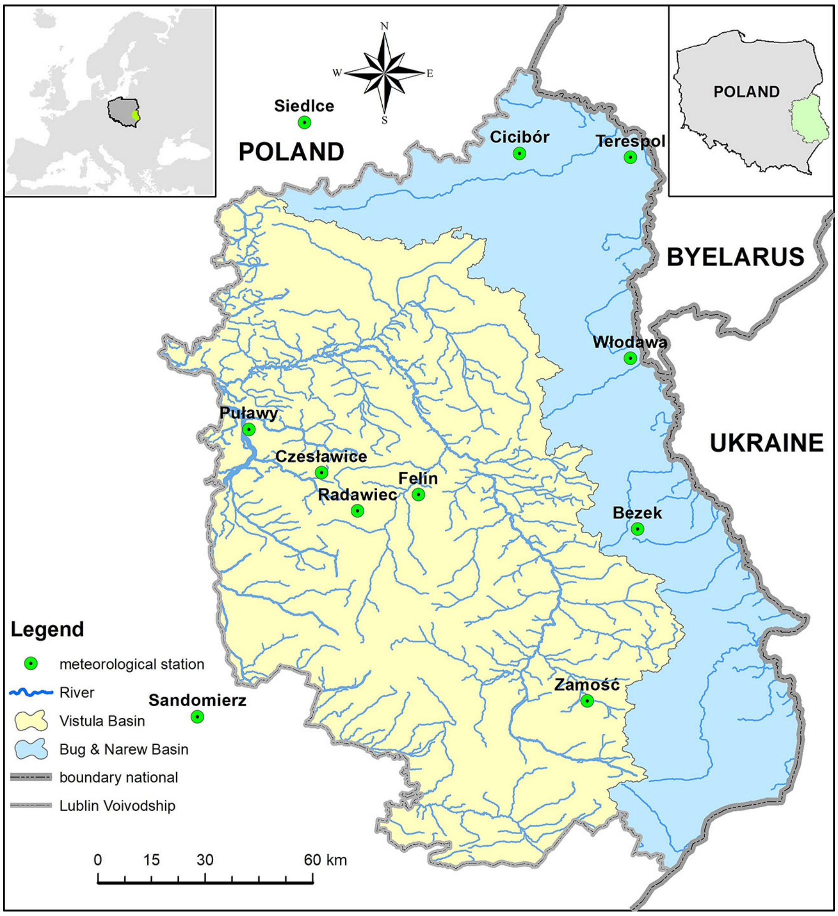

Figure 1. Location of the meteorological stations and the river basins (blue – the Bug and Narew basin, yellow – Vistula basin) in the study area (Lublin Voivodeship, Poland, East-Central Europe)

the University of Life Sciences in Lublin and the Research Centre for Cultivar Testing in Słupia Wielka. The measurement stations were located in central and eastern Poland (in administrative terms, in Lublin Province and its outskirts). For the purpose of obtaining more detailed results, the data originating from stations located outside the Province, however in its immediate vicinity, was also taken into account. The above–mentioned data originated from the meteorological station located in Siedlce and Sandomierz. The locations of meteorological and precipitation stations are presented in Figure 1.

Decadal precipitation needs of the winter wheat cultivated in medium-cohesive soils were analysed in the months from April to July (i.e. from the beginning of the meteorological growing season to full maturity). In the scope of these months, the greatest precipitation needs during vegetation of this cereal occur, while at the same time, high variability and frequent precipitation deficits are observed within this period (Kołodziej et al. 2003; Ziernicka–Wojtaszek and Kopcinska, 2020). It is necessary to emphasise that precipitation needs for plants cultivated in Poland are developed only for the warm half-year, which lasts from April to September (i.e. meteorological vegetation period).

Statistical calculations

The monthly precipitation needs of winter wheat were calculated based on the decadal precipitation needs, developed for Poland by Dzieżyc et al. (1987). Table 1 presents the data concerning the precipitation needs of wheat in the basin areas of two rivers: upper Vistula, Bug, and Narew.

As a result of air temperature variability and progressing climate warming (more and more frequent heat waves and, consequently, intensified droughts), the monthly precipitation needs of winter wheat, which are presented in Table 1, were adjusted according to the method proposed by Klatt and Kac (in: Żakowicz and Hewelke 2002), which assumes that an air temperature increase/decrease by 1 °C causes an increase/decrease in the precipitation needs of plants by an average of 5 mm.

With a change in temperature by 1 °C in relation to the average temperature from the period of 1971–2020, the adjusted precipitation needs (Pw) of winter wheat were calculated, by appropriately decreasing or increasing the precipitation needs determined by Dzieżyc et al. (1987), in the subsequent months of research years. Afterwards, the differences between monthly total precipitation (P_i) and adjusted precipitation needs (P_w) were calculated ($P_i - P_w$). Negative differences meant a deficit, while positive differences meant an excess of precipitation. The subsequent stage of our research consisted of the calculations of standard deviations (σ) of the obtained differences ($P_i - P_w$). Based on the obtained standard deviation values, two classes of the precipitation deficits of winter wheat were distinguished in relation to the values ($P_i - P_w$) = 0. The precipitation deficits, which are described as moderately dry and dry in the subsequent part of our study, were classified according to the method prepared by Skowera et al. (2016).

According to Skowera et al. (2016), the distinguished classes covered the following conditions:

a) moderately dry for deficit values in the range from –0.5σ to –1σ,
b) dry in the case of precipitation deficits below –1σ.

In accordance with the studies of Kalbarczyk (2008), Skowera et al. (2016), and Bartoszek et al. (2021), in which the authors proved that the precipitation needs of plants increase along with the air temperature increase, an assessment was conducted in the scope of changes in the precipitation needs of winter wheat in subsequent decades of the research period (1971–2020). Furthermore, the temporal trends of precipitation needs (reduced as a result of temperature

Table 1. Monthly precipitation needs of winter wheat (mm) in the scope of medium-cohesive soils** in the basins areas of the following rivers: upper Vistula, Bug, and Narew* (Dzieżyc et al., 1987)

River basin areas	April	May	June	July
Vistula	43	57	83	84
Bug and Narew	36	50	69	75

Note: * west of the northwest-southeast line – the research area belongs to the basin area of upper Vistula, while to the east - the research area belongs to the basin area of Bug and Narew; ** medium-cohesive soils are dominant in the Lublin Province.

changes) and the temporal trends of precipitation deficits of winter wheat in the months from April to July were also determined. The temporal trends of precipitation needs were determined according to the non-parametric Mann-Kendall correlation coefficient, which is intended for the identification of downward or upward trends in a data series (Hirsch et al. 1982).

In the case of data for which an upward or downward trend was found, the size of changes in wheat precipitation needs in the next months was estimated by calculating the Sen's slope estimator (Hensel and Hirsch 1992).

The trends of precipitation deficits were determined based on the non–parametric Kendall rank correlation coefficient. Subsequently, the size and frequency of precipitation deficits in the cultivation of winter wheat were calculated. The statistical calculations were carried out with the use of MAKESENS software (Salmi et al. 2002), Office Excel, and Statistica 12.0.

The next stage of our research involved the determination of the relation between precipitation deficits and atmospheric circulation. In order to do this, the calendar of air masses flowing from various directions to the area of central and eastern Poland was used (Bartoszek and Kaszewski 2022). The occurrence of six air masses in the period from April to July was analysed, which differed in terms of temperature and humidity: Arctic air (A), Polar maritime fresh air (mPf), Polar maritime old air (mPo), Polar maritime warm air (mPw), Polar continental air (cP) and Tropical air (T). Furthermore, the values of air temperature at 12 UTC and the number of days without precipitation were averaged for all analysed meteorological stations covered by our research.

RESULTS

In the scope of research years, i.e. 1971–2020, the adjusted precipitation needs of winter wheat in the Lublin Province (Table 2) were similar to the precipitation needs of wheat determined by Dzieżyc et al. (1987) (Table 1).

As a result of the analysis of monthly total precipitation in the area of central and eastern Poland, it was concluded that during the research years (1971–2020), the average adjusted precipitation needs of winter wheat in the period from April to July were secured (Table 1, 2, 3). Nevertheless, while taking into account the temporal and spatial variation of precipitation occurring in the region of Central Europe, it was also observed that there was a high variation of monthly total precipitation in the research area (cv%) (the basin area of Bug and Narew, and upper Vistula) from 1971 to 2020 (Table 3).

As a result of the confirmed spatial and temporal differentiation of monthly total precipitation (Table 3), it was also examined whether, due to the progressing climate warming, there are statistically significant temporal trends of the wheat's precipitation needs. On the basis of calculated Mann-Kendall Z trend coefficients, it was concluded that there are significant increases of the adjusted precipitation needs of wheat in April, June, and July. In May, there was only a slight increase in these needs, which was statistically insignificant (Table 4). In the scope of months, in which a significant increase in the adjusted precipitation needs occurred, the size of this increase was determined based on the Sen's slope estimator (ΔPw per 10 years) (Table 4). An increase of the adjusted precipitation needs of wheat amounted on average from 2.1 to 3.2

Table 2. The adjusted precipitation needs of winter wheat [mm] in the period from 1971 to 2020

River basin areas	April	May	June	July
Bug and Narew	36	50	69	77
Vistula	44	57	84	85

Table 3. Monthly sums (P) and variation of total precipitation (cv%) in the period from 1971 to 2020

River basin areas	Parameter	April	May	June	July
Bug and Narew	P (mm)	35	59	72	77
	cv(%)	45	38	51	47
Vistula	P (mm)	40	65	70	83
	cv%	48	48	45	45

Note: P (mm) – average monthly total precipitation, cv% – coefficient of variation of monthly total precipitation.

Table 4. The values of Mann-Kendall trend (Z test) in the scope of winter wheat's precipitation needs and changes in precipitation needs (ΔPw per 10 years) determined based on the Sen's slope estimate (1971–2020)

Meteorological station	April		May		June		July	
	Test Z	Sen's slope	Test Z	Sen's slope	Test Z	Sen's slope	Test Z	Sen's slope
Siedlce	3.70***	2.5	0.40	0.30	3.16**	2.3	2.60**	2.4
Cicibór	3.92***	2.9	1.31	1.10	4.24***	3.1	3.74***	3.1
Terespol	3.49***	2.5	1.31	1.10	4.24***	3.1	3.74***	3.1
Włodawa	3.92***	2.9	1.31	1.10	4.24***	3.1	3.74***	3.1
Bezek	4.28***	3.2	1.39	1.38	4.40***	3.0	4.16***	3.6
Puławy	3.93***	2.9	1.21	0.90	4.49***	3.0	3.48***	3.0
Czesławice	2.80**	2.1	0.07	0.00	2.80**	1.8	2.91**	2.5
Radawiec	3.68***	2.6	0.92	0.80	4.32***	3.0	3.75***	3.3
Felin	4.21***	3.2	1.91+	1.50	4.97***	3.5	4.50***	3.8
Zamość	3.29**	2.5	0.90	0.80	4.52***	2.8	4.18***	3.2
Sandomierz	4.25***	3.2	1.39	1.00	4.91***	3.2	3.66***	3.0

Note: + $p<0.1$, * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

mm/10 years in April, from 1.8 to 3.5 mm in June and from 2.4 to 3.8 mm per 10 years in July (Table 4).

Precipitation deficits in the cultivation of winter wheat in central and eastern Poland (1971–2020)

The negative values of differences, which meant a precipitation deficit (while positive values meant excess), were identified based on the calculated differences between the actual monthly total precipitation (Pi) and the adjusted precipitation needs (Pw); (Pi–Pw). This study analysed only the values of deficits (i.e. when Pi–Pw<0), because they result from precipitation below the norm or long periods without precipitation, which are usually characterised by a large spatial range, while precipitation above the norm during the summer period is usually short-term and often characterised by only a local range.

It was found that the greatest precipitation deficits in the period from 1971 to 2020 occurred

Table 5. Precipitation deficits (mm) of winter wheat from April to July in central and eastern Poland (1971–2020)

River basins	April	May	June	July
Bug and Narew	–13	–15	–21	–31
Vistula	–18	–16	–31	–32

Table 6. The trends of precipitation deficits in the cultivation of winter wheat from April to July in central and eastern Poland (1971–2020)

Meteorological station	April	May	June	July
Siedlce	–0.11	0.01	–0.18	–0.08
Cicibór	–0.25*	0.07	0.01	0.01
Terespol	–0.21*	–0.02	–0.12	–0.02
Włodawa	–0.23*	0.01	–0.14	–0.21*
Bezek	–0.20	0.06	–0.16	–0.10
Puławy	–0.18	–0.11	–0.20*	–0.07
Czesławice	–0.11	0.01	–0.27	–0.14
Radawiec	–0.19*	–0.02	–0.18	–0.01
Felin	–0.22*	–0.02	–0.18	–0.01
Zamość	–0.09	–0.13	–0.37*	–0.06
Sandomierz	–0.14	–0.11	–0.30*	–0.08

Note: * significant trend for $p< 0.05$.

in June and July, at the stations located in the basin area of upper Vistula, and they on average amounted to: –32 mm, –31 mm. The smallest average precipitation deficits were observed in April and May, in the basin area of the Bug and Narew rivers: –13 mm, –15 mm (Table 5).

In the scope of the number of precipitation deficits, it was verified whether the deficit trends occur in subsequent months (April–July). As a result, a significant trend of precipitation deficits in the basin area of the Bug and Narew rivers was found only in the case of 3 meteorological stations in April and in 1 meteorological station in July. In the scope of stations located in the area of upper Vistula, a significant increase in precipitation deficits was found in 2 stations in April and 3 meteorological stations in June (Table 6).

The box plots (frame–whiskers) were drawn up in order to illustrate the dynamics of the size and range of variation of the winter wheat's precipitation deficits occurring in the area of central and eastern Poland (Figure 2).

It was concluded that precipitation deficits increased adequately to the growth of the wheat's precipitation needs. They varied in temporal and spatial terms. The greatest precipitation deficits in the period from April to July (1971–2020) were observed at the meteorological stations located in the western (Puławy, Sandomierz) and central–western part of our research area (Lublin–Felin, Radawiec, Czesławice). The greatest precipitation deficit as well as the variation range were observed in June and July (Figure 2).

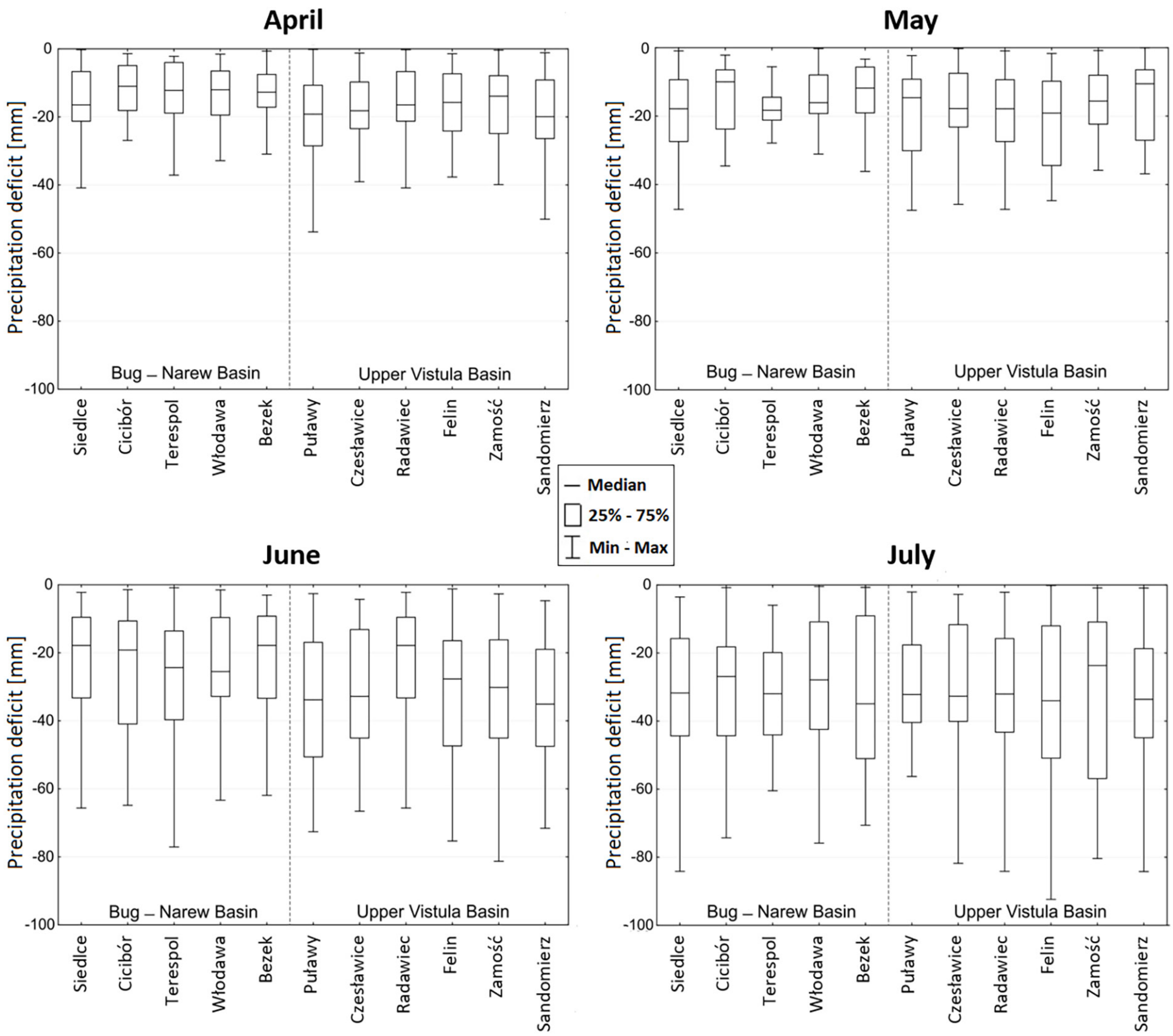

Figure 2. The size and range of variation of the winter wheat's precipitation deficits (mm) in the area of central and eastern Poland (1971–2020). Boxes: 25, median, 75 percentiles. Whiskers: min-max values

Frequency of the occurrence of precipitation deficits of winter wheat in central and eastern Poland (1971–2020)

Frequency of the occurrence of precipitation deficits determined in our study as moderately dry and dry conditions is presented in Figure 3. On the basis of the calculated frequency of precipitation deficits in the distinguished classes, it was found that dry conditions (precipitation deficit below –1σ) and moderately dry conditions (precipitation deficit in the range from –0.5σ to –1σ) occurred in all months of the studied period with varying frequency (from 16% in May to 56% in June). Furthermore, the precipitation deficits classified as dry conditions most often occurred in June and April at the following meteorological stations: Puławy and Sandomierz (the basin area of upper Vistula), while moderately dry conditions were dominant in July and May in all meteorological stations of the research area, with the lowest frequency of precipitation deficits (dry and moderately dry conditions) observed in May (Figure 3), which is a critical month in the cultivation of wheat (i.e. winter wheat has the highest water demand in May).

Synoptic background of the occurrence of precipitation deficits from April to July (1971–2020)

Over the area of central and eastern Poland in the period from April to July, the polar maritime old air (mPo) occurs most often, and while moving slowly from the Atlantic Ocean through Western Europe, it undergoes a clear transformation and acquires the characteristics that are average for the analysed area. The total share of all maritime air mass varieties (mPo, mPf, and mPw) amounts to approx. 66% (Figure 4). Noticeably lower frequency of the occurrence was observed for the continental air (cP) coming from the eastern sector (from Ukraine and Russia), as well as for the arctic air (A) and the tropical air (T) coming from the north and from lower latitudes, respectively.

The largest share of days without precipitation and the highest average air temperature in the period from April to July were observed in the scope of two masses with continental characteristics, i.e. cP and T, but also mPw that flows from the Atlantic Ocean, located west of the Iberian Peninsula (Figure 5). A noticeably greater number of days with precipitation is observed during the occurrence of

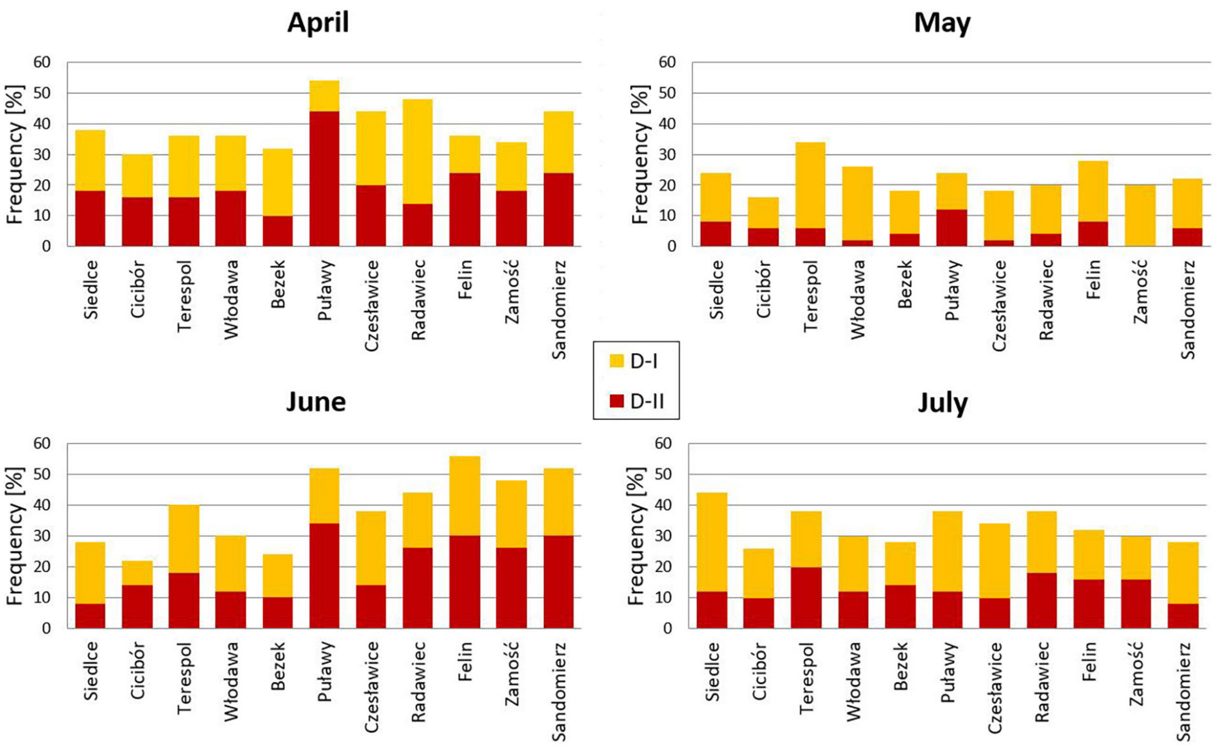

Figure 3. Frequency (%) of the occurrence of precipitation deficits in central and eastern Poland (1971–2020). D-I – moderately dry conditions for deficit values in the range from –0.5σ to –1σ, D-II – dry conditions in the scope of precipitation deficits below –1σ

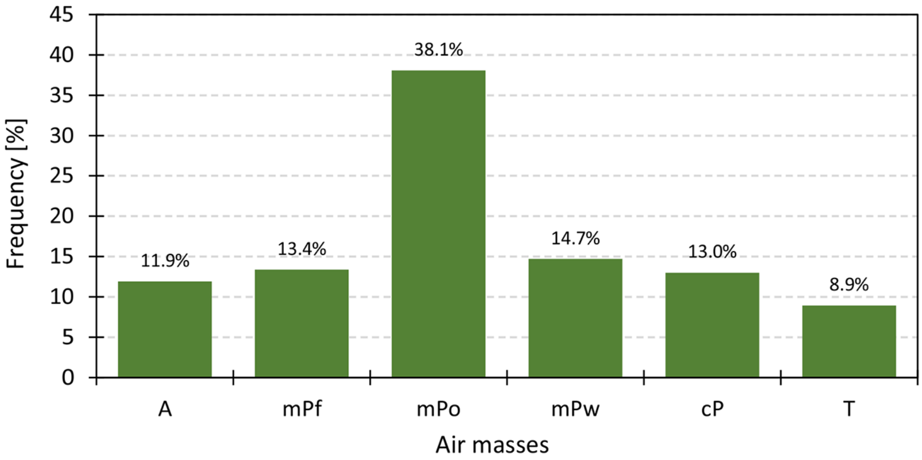

Figure 4. Frequency (%) of the occurrence of individual air masses over central and eastern Poland in the period from April to July (1971–2020). Arctic air (A), Polar maritime fresh air (mPf), Polar maritime old air (mPo), Polar maritime warm air (mPw), Polar continental air (cP) and Tropical air (T)

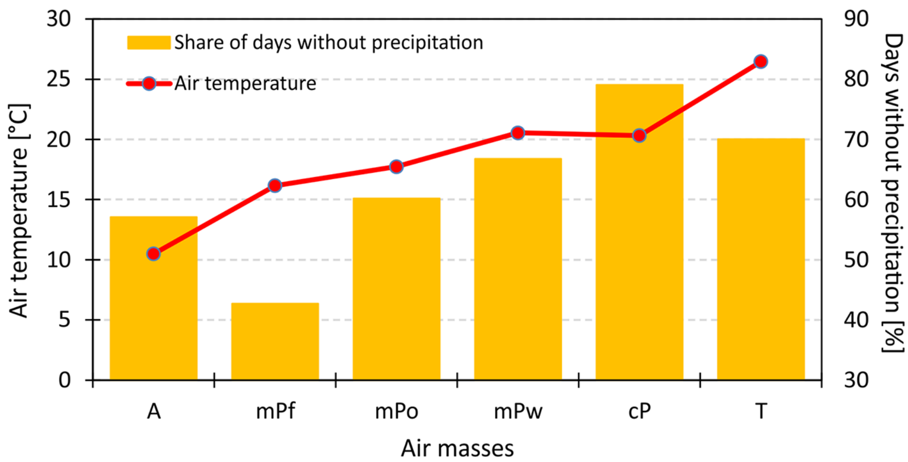

Figure 5. The average air temperature value (ºC) at 12 UTC and the share of days without precipitation (%) during the occurrence of air masses in central and eastern Poland in the period from April to July (1971–2020)

cooler air masses, which flow from the North Atlantic (mPf) and from the Arctic Circle (A).

In the period from 1971 to 2020, statistically significant changes were found in the frequency of the occurrence of most air masses over the research area in the months from April to July. The number of days with warm air masses significantly increased, i.e. T (+2.1 days per 10 years; $p<0.01$) and mPw (+3.2 days per 10 years; $p<0.01$). The share of arctic air masses (–1.9 per 10 years; $p<0.01$) and mPo (–1.8 per 10 years; $p<0.05$) decreased. To a certain extent, the above–mentioned changes translated into an increase in air temperature at 12 UTC (+0.22 °C per 10 years; $p<0.01$), as well as into an increase in the number of days without precipitation (+1.4 days per 10 years; $p<0.05$). It should be emphasised that the greatest increase in temperature was recorded among 2 of the 3 warmest masses, i.e. T (+0.95 °C per 10 years; $p<0.01$) and mPw (+0.54 °C per 10 years; $p<0.01$). No significant changes in frequency and temperature were found in the case of continental air (cP).

DISCUSSION

Although climate changes have always occurred, the pace of these changes in the 21st century has become particularly rapid, and warming is the most distinguishing feature of modern climate changes. In accordance with the Reports of the Intergovernmental Panel on Climate Change (2007), the global temperature has been higher in each subsequent decade compared to the previous one. Since 1861, the global air temperature has increased by 0.6 °C, while as much as half of the observed increase took place in the last 30 years.

According to Wibig (2020), precipitation is characterised by considerable variability, both in temporal and spatial terms. Nevertheless, precipitation does not change as intensively as temperature. In addition, some regions of the world note downward trends, while other regions note upward trends in this scope. However, over a longer period (1901–2008), slight upward trends in precipitation were dominant on the global scale. Since the middle of the 20th century, mainly downward trends – although statistically insignificant – have been observed in this scope. Moreover, warming also contributes to the occurrence of extreme precipitation events (Lenderink and Meijgaard, 2008).

The research concerning Poland's climate change demonstrates that the average annual temperature is continuously rising. Ziernicka–Wojtaszek and Kopcińska (2020) emphasise that there is a clear tendency documented in Poland in the scope of temperature increase, as well as increase in precipitation variability and decrease in summer total precipitation.

Bartoszek et al. (2021) demonstrated that the occurrence of drought in the Lublin region during the growing season is associated with a statistically significant increase in air temperature in April, June, July, and August, as well as the lack of trends in the scope of precipitation changes in the warm half–year.

It is necessary to emphasise that in 2022, the cultivation of winter cereals was at risk of drought in 97.65% of communes in the Lublin Province, while the share of arable land at risk of drought amounted to 37.89% (Instytut Uprawy Nawożenia i Gleboznawstwa, 2022). However, the irrigation of agricultural plants in Poland - unlike in the countries located in warmer climate zones - is essentially of an intervention nature and supplements the periodic precipitation deficits in relation to the water requirements of crops. Although in the case of soils characterised by very low water retention, irrigation can constitute the primary yield-creating factor, which ensures the achievement of stable yields. The irrigation of winter wheat - cultivated on soils characterised by low water retention - during dry periods is sometimes justified in terms of production, however, the profitability of this procedure is usually low in our country (Rzekanowski et al. 2011; Żarski, 2009).

High precipitation variability in individual years, which is characteristic of the climate in Poland, results in the fact that optimal total values of precipitation and their distribution, compliant with, or similar to the requirements of crops, occur rarely.

In the case of winter wheat, the period of the greatest sensitivity to precipitation deficit is the phase between stem formation and earing, which occurs in the period from mid–May to the beginning of June (Podolska, 2018; Dzieżyc, 1989).

During the analysis of the adjusted precipitation needs of winter wheat in central and eastern Poland (1971–2020), it was observed that the above–mentioned needs were varied in temporal and spatial terms. Moreover, significant increases of the adjusted precipitation needs of wheat in April, June, and July were found, while statistically insignificant small increases in these needs were observed in May (Table 2). The above–mentioned results are consistent with the research of other authors, who concluded that precipitation does not show upward trends, however air temperature increases, and therefore the precipitation needs of plants are greater (Michalska, 2011; Bartoszek et al. 2021). Wibig (2020) found that the average annual temperature in Poland increased at a rate of 0.28 °C/10 years in the period from 1951 to 2019.

The research showed that the precipitation needs of wheat increased adequately to the increase in precipitation deficits. The greatest deficits of the wheat's precipitation needs were observed in June and July at the stations located in the basin area of upper Vistula, and on average they amounted to: –32 mm, –31 mm. The smallest average deficits of these needs were observed in April and May, in the basin area of the Bug and Narew rivers: –13 mm, –15 mm (Table 5, Figure 2).

Despite the fact that there were no clear changes, the precipitation regime was subject to certain modifications in the second half of the 20th century and at the beginning of the 21st century, i.e. the precipitation variability coefficient increased, while the share of summer total precipitation decreased in the scope of annual total precipitation. Moreover, according to Czarnecka and Niedzgorska–Lencewicz (2012), a common phenomenon in most of Poland consists of an upward trend of precipitation during spring and autumn seasons, and a decreasing share of summer precipitation in the annual total precipitation. According to Kołodziej et al. (2003), the average total precipitation over fifty years (1951–2000) in the Lublin region was lower in relation to the precipitation needs of crops.

While analysing the frequency of the occurrence of precipitation deficits, which are defined in our research as moderately dry and dry conditions (Figure 3), it was found that dry conditions (with precipitation deficits below -1σ) and moderately dry conditions (for values of deficits in the range from -0.5σ to -1σ) occurred in all months of the analysed period with varying frequency (from 16% in May to 56% in June). The results of our research are consistent with the research of other authors. Based on the conducted research on precipitation deficits in the spring months, Kalbarczyk and Kalbarczyk (2022) also found that in Poland there are smaller precipitation deficits in May compared to April and March. Bartoszek et al. (2021) found no upward trends of temperature and locally weak upward trends of precipitation in May in the Lublin region.

The research demonstrated that change in the frequency of air masses inflow over central and eastern Poland had some impact on the increase in precipitation deficits in the cultivation of wheat, which is consistent with the research of Bartoszek and Kaszewski (2022). During the warm half of the year, the number of days with more humid air masses decreased, while the share of days with air masses coming from lower latitudes, which bring warming and decrease the probability of precipitation, significantly increased. Furthermore, the research demonstrated that the temperature of these masses noticeably increased compared to the second half of the 20th century, which constitutes the result of progressive climate warming, primarily caused by human activity (Intergovernmental Panel on Climate Change, 2007). The frequency of the occurrence of low stratiform clouds has clearly decreased in the last two decades in Poland (Matuszko et al. 2022), which translated into significant increases in sunshine duration in the spring and summer seasons (Bartoszek et al. 2020). As a result, the increased net solar flux at the surface contributed to the increase in evapotranspiration, as well as the reduction of water resources in soil in the research area (Somorowska, 2022). In turn, stronger heating of the ground is often conducive to the formation of a greater number of heavy vertical convective clouds, which are characterised by short-term but intense precipitation (Luo et al. 2023). In such case, most of the rainwater evaporates or flows off, and as a result, it is not available to plants. The research by Pińskwar et al. (2019) indicates an increase in the frequency of intense precipitation, as well as a decrease in the number of days with precipitation in Poland.

Along with the predicted further increase in air temperature, as well as the progressing change in the structure of precipitation (lower share of uniform precipitation, increase in intensive precipitation), an intensification of unfavourable conditions for the cultivation of winter wheat in central and eastern Poland should be expected. Due to the growing climate risk, it is necessary to prepare the agricultural measures that will allow to adapt to climate changes, particularly in the scope of production of plants.

CONCLUSIONS

Based on the research conducted in the area of central and eastern Poland in the period from 1971 to 2020, both spatial and temporal differences were found in the scope of the amount and frequency of precipitation deficits in the cultivation of winter wheat.

The precipitation deficits occurring in the north-eastern part of the research area (the basin area of the Bug and Narew rivers) were smaller compared to the western part (the basin area of upper Vistula), which may be characterised by practical significance in terms of the regionalisation of wheat cultivation.

The lowest risk of precipitation deficits was found in May (from 15% to 32%), while the highest risk of precipitation deficits was observed in June (from 22% to 56%).

Change in the frequency of air mass inflow was one of the factors that affected the amount and frequency of precipitation deficits in the cultivation of wheat in central and eastern Poland. The number of days with warm and dry air masses flowing from the lower latitudes has increased in a clear manner, while the inflow frequency of cooler and more humid air from the western and northern sectors has decreased.

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